1. Science aim/goal

Utilize the unique power of the infrared fine-structure emission lines to trace the rise of metals from the first galaxies until today.

(i) Scientific Importance: The present day Universe is rich in metals heavier than helium that enable efficient cooling of gas in the ISM in order to form stars, create planets and make the building blocks of life as we know it. The Universe did not start in this state – we know that metals had to build up over time with successive generations of stars. Beyond this broad picture we have very little detail. Extensive studies of metallicity locally and out to z~1 indicate a factor of 10 fall in metallicity, while our knowledge beyond z~1 are much more limited. What little we do know the highest redshifts, $z \gtrsim 4$, is constrained only from quasar absorption spectra. This current state of metallicity studies is unlikely to change in the next 10–15 years. Studies utilizing optical gas-phase nebular emission lines, the "standard" method, have significant degeneracies with ionization state, temperature, and radiation fields in the nebula, leading to greater than a factor of 5 systematic variations between different indicators (left panel of figure). Employing indicators without these degeneracies is vitally important for high-z studies in which physical conditions may be significantly different than in nearby systems. Additionally, optical tracers that are strongly affected by dust extinction will miss the dusty galaxies which are known to be important at high-z. Obtaining a complete understanding of the rise of metals requires a study of metallicity across cosmic time utilizing the mid- and far-IR fine-structure emission lines, which are not susceptible to dust extinction and the degeneracies of optical tracers.

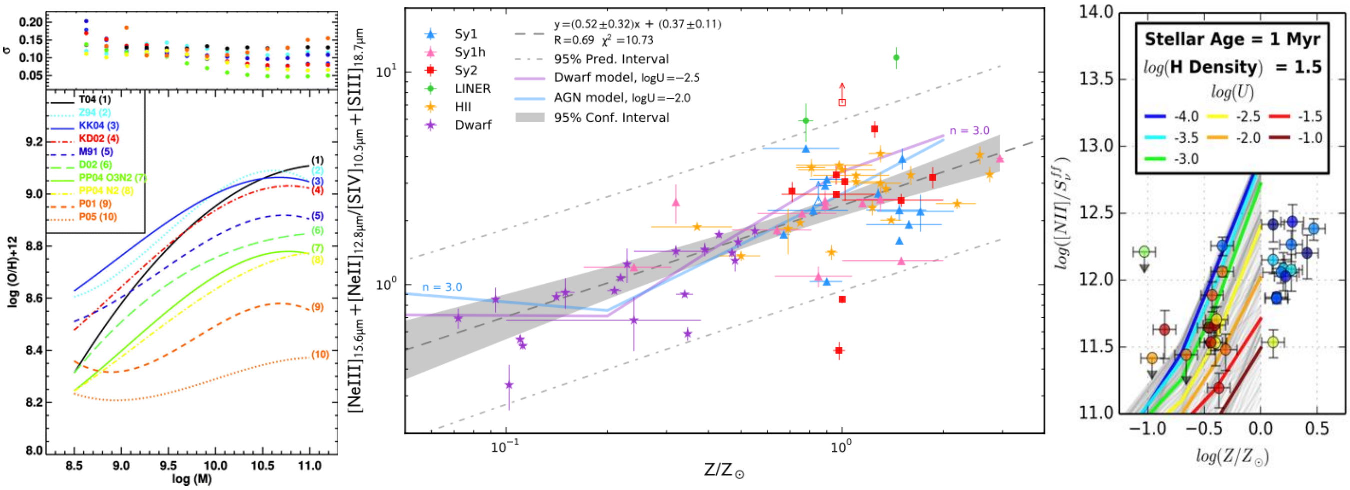
(ii) Measurements Required: Two surveys are required. A primary survey detecting the mid-IR lines (i.e. ([NeII]+[NeIII])/([SIII]+[SIV]); a relative metallicity indicator (middle panel of figure) in tens of thousands of galaxies to build a statistically significant sample. We require ~100 galaxies in each bin, spanning 10 redshift bins from z~0 to 10, with at least three bins in galaxy luminosity, and at least three metallicity bins for each redshift. The second survey will provide absolute metallicity calibration by targeting ~1,000 galaxies from the across parameter space of the large survey for observations of the [OIII] 88μm and [NIII] 122μm lines in galaxies. These will be combined with radio-recombination and/or thermal free-free radio continuum observations by ground based facilities (e.g. JVLA, SKA), which is necessary to calibrate the relative indicators to absolute abundances (see right panel of figure), since one cannot assume local calibrations apply to all redshifts.

(iii) Uniqueness to 10μm to few mm wavelength facility: The mid- and far-infrared and FIR Surveyor is the *only* facility capable of answering these questions. The mid- and far-IR spectral lines used for tracing metallicity are not susceptible to the same degeneracies as the optical lines, making them ideal for studying the evolution of metallicity in the Universe. Other facilities have important synergies, and will help fill in the picture, but a FIR facility is the only one capable of investigating the rise of metals across all of cosmic time utilizing a single relative abundance indicator to minimize systematics. Combined with ground based radio observations, the Surveyor can also place these abundances on an absolute scale. FIR Surveyor combines the necessary wavelength coverage, sensitivity and survey speed to make the study possible.

(iv) Longevity/Durability: JWST is expected to trace both stellar and nebular abundances, but will only do so for few sources. Furthermore, its shortest observable wavelength is 1μm (at intermediate resolving power of R=1000), preventing it from applying the same metallicity indicators to low-z systems as at high-z. JWST does have the spectral coverage to target the mid-IR lines in nearby systems. WFIRST will be will provide spectra of thousands of galaxies, but again will be limited to use of rest frame optical nebular lines and subsequent galaxy redshifts below $z \lesssim 2$. Lastly, ALMA will contribute to our knowledge of the rise of metals, though primarily in sources at z>5, because ALMA is significantly less sensitive that the FIR Surveyor out to 700μm (limiting the number and luminosity of sources observed at lower redshifts). This combined with the challenges of submillimeter observations from the ground, at the very most

ALMA could detect 1000 far-IR fine structure lines from z~1-4 sources in the next 10–15 years. None of these current and expected missions will be able to provide the statistically significant and unbiased observations across cosmic history that are necessary to build a complete picture of the rise of metals, only the FIR Survey is capable of taking such a picture.

3. Figure:



Left: Mass metallicity relation (from Kewley et al. 2008) for ten different optical metallicity indicators using the same galaxy sample and showing 0.7 dex variation amongst the indicators. *Middle:* Relative abundance indicator ([Ne III]15.6+[Ne II]12.8)/([S IV]10.5+[S III]18.7) vs optical metallicities from Fernández-Ontiveros et al. (2016) demonstrating how the line ratio is a tracer of metallicity. *Right:* absolute abundance indicator, [NII] 122μm line to radio free-free continuum ratio versus optical metallicities.

4. Table:

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	μm	10–400	10–800	(a)
Number of targets		10^4	$2x10^4$	
Survey area	deg.^{2}	60	120	(b)
Angular resolution	arcsec	5	2	(c)
Spectral resolution	Δλ/λ	500	1000	Match to galaxy velocity width
Bandwidth		30%	70%	(d)
Spectral line sensitivity	W m^{-2}	1E-21	1E-21	5-σ detection in 1 hour
Signal –to-noise		5	10	Enough for accurate line fluxes
Field of Regard	arcmin^2	100	1000	(e)
Notes: (a) Cover key MIR & FIR lines to z~0-5, ideally to z~8 and cover ALMA bands 10, 9, and 8; (b) In each redshift decade out to z~6 we expect >100 ULIRGs and >1000 LIRGs per square degree (from Bethermin et al. 2012); (c) Since this is a spectroscopic study confusion is not concern, though higher resolution is desired to resolve source multipilicity ; (d) Fractional bandwidth per band, allowing multiple line detections per pointing; (e) Maximize survey speed with many galaxies per pointing				

5. Key references:

1. Kewley, L. J., & Ellison, S. L. (2008). ApJ, 681(2), 1183. http://doi.org/10.1086/587500
2. Herter, T., et al. (1981). ApJ 250, 186–199. http://doi.org/10.1086/159361
3. Fernández-Ontiveros, J. A. et al (2016). arXiv: 1607.02511 http://arxiv.org/abs/1607.02511\

6. Appendix

Sensitivity Estimates

The most useful diagnostic fine structure lines have widths of ~300 km/s integrated over entire galaxies, so that the ideal sensitivity is achieved by matching the spectral resolving power to the linewidth (i.e. *R*~500–1000). Scaling the FIR fine structure lines from local systems (Spinoglio et al. 2013): [NeII]/LIR = 5E-4, [NeII]/LIR = 2E-4, [SIII]/LIR = 5E-4, [SIV]/LIR = 2E-4, [OIII] 52/LIR = 3E-3, [OIII] 88/LIR = 2E-3, [NIII] 57/LIR = 2E-3, [NII] 122/LIR = 2E-4, [CII]/LIR = 2E-3. The line fluxes for all lines are $\lesssim$ 1E-21 W m^{-2} for all ULIRGS ($L_{IR} > 10^{12} L_\odot$) out to z~8, $\lesssim$ 1E-21 W m^{-2} for LIRGS ($10^{11} L_\odot < L_{IR} < 10^{12} L_\odot$) and $\lesssim$ 1E-21 W m^{-2} out to z ~ 2 for sub-LIRGS ($10^{10} L_\odot < L_{IR} < 10^{12} L_\odot$). As such we require FIR Surveyor sensitivity of 1E-21 W m^{-2}, 5-sigma in 1hr observations with R~500.

ALMA expectations

The FIR Surveyor is quite competitive with ALMA, especially in the submillimeter—ALMA Bands 8, 9, and 10 (645, 450 and 350 microns respectively). ALMA faces several challenges that will ensure the FIR Surveyor science and capabilities will be relevant still in 10 to 15 years. First ALMA's sensitivity in these bands is significantly worse than FIR surveyor, even the smallest surveyor of 5m primary would be ~10x more sensitive than ALMA at 350 and 450 microns. Additionally, the atmospheric absorption makes it challenging if not impossible to observe all of the mid- and far-IR fine-structure lines from a galaxies, limiting the science. Second, ALMA's largest beams in submillimeter are ~0.3" so that nearly all sources will be resolved. Also the maximum recoverable scales are ~3" so lensed galaxies and large sources at high-z may be resolved out. Lastly, submillimeter observations with ALMA require the best weather conditions even for the most compact configurations. Currently only 10%, 10% and 20% of the year has weather conditions adequate for band 10, 9 and 8 observations respectively. This means the likelihood of even an accepted high-z ALMA proposal in bands 8, 9 or 10 being observed is low.

With these thoughts in mind, one can estimate the number of far-IR fine structure lines that ALMA could likely detect in one year in Bands 8, 9 and 10. Assuming optimistically that 20% of the year has weather good enough and observations are done only at night gives ~36 days, 24-hour a day in a year. But about half the time ALMA will be in too extended a configuration to be useful for high-z observations reducing the available time by 50%. One then might expect ~80% execution success rate once weather is taken out. Accounting for calibration overheads in these bands gives an estimated "on-source" efficiency of 60% reducing the total available time to ~9 days in a year (~200 hours).

Assuming line luminosities as seen for [CII] one can estimate the number of detections given that available time. Based on Fig. 8 in Herrera-Camus et al. (2015) it is possible to detect [CII] or similarly luminous line from a ULIRG in ~10 mins if a source is not resolved into multiple beams. Given ALMA beams sizes sources are likely to be resolved, as such detections will require 40 - 60 minutes per line per source. If ½ of the total available submillimeter time could be used for high-z fine-structure line detections then ~100 lines could be detected per year. If one wants to observe multiple lines from the same source, then the actual number of galaxies studied would be significantly less.